TRANSACTIONS OF THE 12TH CARIBBEAN GEOLOGICAL CONFERENCE

ST. CROIX, U.S. VIRGIN ISLANDS

August 7th - 11th, 1989

12a Conferencia Geologica del Caribe

12th Caribbean Geological Conference

St. Croix

7th - 11th August, 1989

U.S. Virgin Islands

12me Conference Geologique de Caraibes

Edited by

David K. Larue
Department of Geology, University of Puerto Rico
Mayagüez, PR 00708, Puerto Rico

and

Grenville Draper
Department of Geology, Florida International University
Miami, FL 33199
U.S.A.

Additional copies of this book may be purchased from

Miami Geological Society
P.O. Box 431552
South Miami, FL 33243, U.S.A.

December 1990

DEPTH OF EMPLACEMENT OF GRANITOID PLUTONIC ROCKS IN THE EASTERN GREATER ANTILLES ISLAND ARC

Edward G. Lidiak
Department of Geology and Planetary Science
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

ABSTRACT

Electron-microprobe analyses of magmatic hornblende from granitoid rocks of the Morovis stock, San Lorenzo batholith, Vieques pluton, Utuado pluton, Rio Blanco stock, and Virgin Islands batholith have been carried out for the purpose of estimating the pressure at which the intrusions were emplaced. The intrusions have calc-alkalic chemical affinities and consist mainly of granodiorite and quartz monzodiorite, with lesser amounts of quartz diorite, tonalite, and gabbro. Hornblende, with different Al content in the various plutons, typically occurs in association with quartz, plagioclase, K-feldspar, biotite, magnetite, and sphene.

Analyses of the total Al content of hornblende, which may be used as an empirical geobarometer, suggest that the intrusions were emplaced at low to medium pressures and show a progressive decrease in depth of emplacement from about 10 km for the oldest pluton to about 4 km for the youngest pluton. These geobarometric data help characterize the evolution of the crust in the eastern Greater Antilles island arc in late Cretaceous and early Tertiary time and indicate an average uplift rate of 0.01-0.02 cm/yr.

INTRODUCTION

The Caribbean region encompasses a complex of Cretaceous to Cenozoic island arc rocks which includes both active and inactive arc segments that developed by interaction of the Pacific, proto-Caribbean, and Atlantic oceanic plates, the Caribbean oceanic plateau, and the bounding continental plates (Burke, 1988; Donnelly, 1989). Each of the various arc segments or terranes that are presently preserved evolved in response to a related series of tectonic events but each has its own geological, geochemical, and geophysical characteristics. Considerable attention has justifiably been given to reconstruction of the Caribbean plate and its highly mobile history in which various geologic elements have been displaced by hundreds of kilometers.

Also of considerable interest is the origin and evolution of the Caribbean lithosphere and specifically its crust. Seismic refraction studies (Officer and others, 1959; Edgar and others, 1971; Boynton and others, 1979) have demonstrated that the Caribbean crust is thicker than typical oceanic crust and that beneath islands such as Puerto Rico crustal thickness approaches 30-35 km. It seems evident that if the Caribbean evolved as an ocean-ocean arc system as most researchers have proposed, then the thickened Caribbean crust owes its origin not only to tectonic processes but also to igneous and metamorphic processes that occurred during island arc formation. Knowledge of the composition as well as the intensive parameters of temperature and pressure are thus critical to understanding the origin of the crust in the Caribbean as these parameters can provide constraints on the evolution of the various rock systems.

The igneous geology of the Caribbean region has been summarized in a series of papers by Donnelly (Donnelly and Rogers, 1978; Donnelly and Rogers, 1980; Donnelly and others, 1990). Most of the research has been carried out on the volcanic rocks which include oceanic plateau basalts, primitive island arc suite, calc-alkaline suites, and rift-related suites. Comparatively little emphasis has been given to the intrusive rocks, and only limited data are available.

In this paper some preliminary results are presented on the chemical mineralogy of hornblende from a suite of granitoid plutons in Puerto Rico, including Vieques, and the nearby Virgin Islands with the purpose of presenting estimates on the pressures (and depths) at which the plutons were emplaced. The use of hornblende as a geobarometer is based on the correlation between the total Al (Al^T) content of hornblende and the estimated pressures of crystallization of calc-alkaline plutons (Hammarstrom and Zen, 1986; Hollister and others, 1987; Rutter and others, 1989). Data of this type which permit the estimation of depths of plutonic emplacement and the average rates of uplift since late Cretaceous time have not previously been published for any igneous rocks in the Caribbean region.

GEOLOGIC SETTING

Puerto Rico and the Virgin Islands form the eastern part of the inactive Greater Antilles island arc. The earliest arc deposits are the pre-Albian submarine keratophyres and spilites (Water Island Formation) of the Virgin Islands and their pre-Robles equivalents of Puerto Rico. These rocks comprise the primitive island arc suite of Donnelly and Rogers (1980). The primitive suite is overlain by Albian to Paleocene shallow-water submarine and terrestrial deposits with distinct calc-alkaline affinities and which reflect an emergent island arc. The main granitoid plutons, which are the topic of this report, were emplaced during this second main phase of arc evolution. The intrusive igneous activity in Puerto Rico occurred mainly during late Cretaceous time but continued on a lesser scale into the Eocene. Plutonism in the Virgin Islands continued into the Oligocene. Active vulcanism ceased by late Oligocene time and was succeeded by platform-type clastic and carbonate sedimentation.

The plutons discussed in this report are, from west to east, the Utuado pluton, Morovis stock, San Lorenzo batholith, Rio Blanco stock, Vieques pluton, and Virgin Islands batholith (Figure 1). They occupy the core of the eastern Greater Antilles island arc. The plutons vary in size and compositional complexity from the large San Lorenzo batholith having an outcrop area of 500 km^2 and composed of at least three distinct compositional units, through the medium-size Utuado pluton with an outcrop area of about 200 km^2 and containing two mappable units, to the smaller and essentially compositionally uniform Morovis and Rio Blanco stocks each having outcrop areas of about 20 km^2 (Cox and others, 1977; Kesler and Sutter, 1979). The Virgin Islands batholith occupies about 35 km^2 of land area, but large parts of the batholith may be submerged (Longshore, 1965). It is compositionally diverse.

The effects of contact metamorphism along the margins of the plutons are minor. Assemblages corresponding to the hornblende hornfels facies are present locally adjacent to the San Lorenzo batholith (Fettke, 1924), the Utuado pluton (Chen, 1969), and the Rio Blanco stock (Seiders, 1971). Both hornblende hornfels and pyroxene hornfels occur locally adjacent to the Virgin Islands batholith (Longshore, 1965). Pressure

Larue, D.K., and Draper, G. (eds.), ***Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S.V.I.***, Miami Geological Society, P.O. Box 431552, South Miami, FL 33243, U.S.A

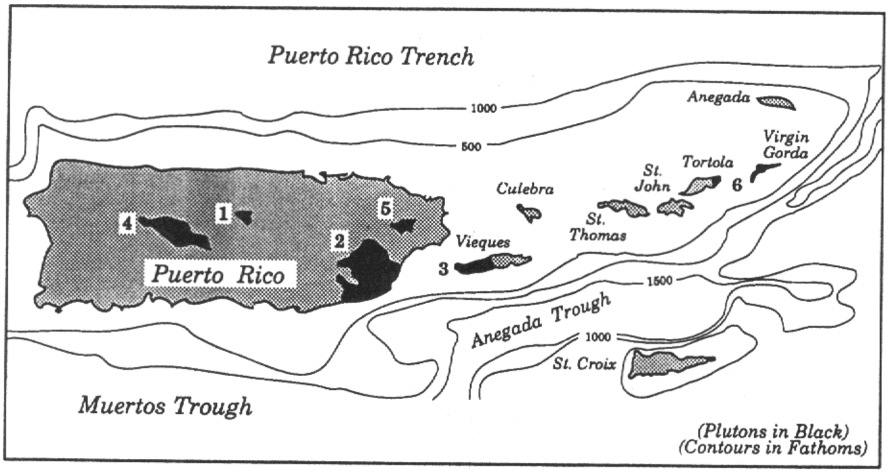

Figure 1. Location map of Puerto Rico and the Virgin Islands. Plutons discussed in text: 1, Morovis stock; 2, San Lorenzo batholith; 3, Vieques pluton; 4, Utuado pluton; 5, Rio Blanco stock; 6, Virgin Islands batholith.

estimates based on critical mineral assemblages from the contact aureoles are not presently available. Longshore (1965), however, on the basis of general facies associations, concluded that pressures were 1-3 kbar during contact metamorphism of the Virgin Islands batholith. Field relationships suggest that the other plutons were also emplaced at shallow levels.

Samples used in this study were selected in so far as possible on (1) the basis of location within the interior of each pluton and away from possible thermal effects of later igneous activity, (2) lack of alteration (both surficial and otherwise), and (3) their being compositionally representative of the main phase or phases of each pluton. The U. S. Geological Survey quadrangle maps were used where available for geologic control.

ANALYTICAL METHODS

Hornblende crystals were analyzed for Si, Al, Ti, Cr, Fe (total), Mn, Mg, Ca, Na, and K using an automated CAMECA SX-50 electron probe microanalyser fitted with four wavelength dispersive spectrometers and one energy dispersive spectrometer. Operating conditions were set at 15-kV accelerating voltage and 20 nannoamps beam current and with a spectrum accumulation time of 20 seconds.

Between three and six different thin sections (rock samples) from each pluton were analyzed. For samples used in the pressure determinations, at least two hornblende crystals were examined in each thin section and a minimum of eight separate spot analyses were made of each thin section. Results are summarized in Tables 1 and 2. Hornblende analyses reported here are from the rims of crystals, all analyses being from within 20 μm of a crystal edge. Systematic study of the interiors of hornblende crystals were not carried out as part of this study; however, it is apparent from random spot analyses that the hornblende is typically zoned with respect to Si, Al, Fe, and Mg.

APPLICABILITY OF THE GEOBAROMETER

The hornblende geobarometer proposed by Hammarstrom and Zen (1986) is based on the correlation between estimated pressures of crystallization of calc-alkalic granitoid rocks and the Al^T content of hornblende. For the geobarometer to be applicable to a suite of calc-alkalic plutons, the following conditions should be satisfied (Hammarstrom and Zen, 1986; Hollister and others, 1987): (1) bulk rocks must have calc-alkalic compositions; (2) hornblende must be magmatic and not modified by sub-solidus reaction; (3) the primary phases quartz, plagioclase, K-feldspar, hornblende, biotite, sphene, and magnetite must be co-magmatic; (4) hornblende rims only should be used in order to reflect more closely final crystallization conditions; (5) plagioclase compositions should be essentially constant; and (6) pressures of emplacement should be greater than ~2 kbars to reduce the effects of temperature variability. The hornblende studied by Hammarstrom and Zen (1986) show a strong linear correlation between Al^T and Al^{iv}, and they determined that the correlation between pressure and Al^T in hornblende can be described by the linear regression $P = -3.92 + 5.03Al^T$. This regression equation is used in the present paper to calculate pressures of emplacement.

HORNBLENDE COMPOSITIONS

Average hornblende analyses that were used in the pressure calculations are listed in Table 1. Cation proportions were calculated on a basis of 23 oxygens, with total Fe as FeO. Total Al in these hornblende crystals varies from a high of 1.36 cations in the Morovis stock to a low of 0.99 cations in the Virgin Islands

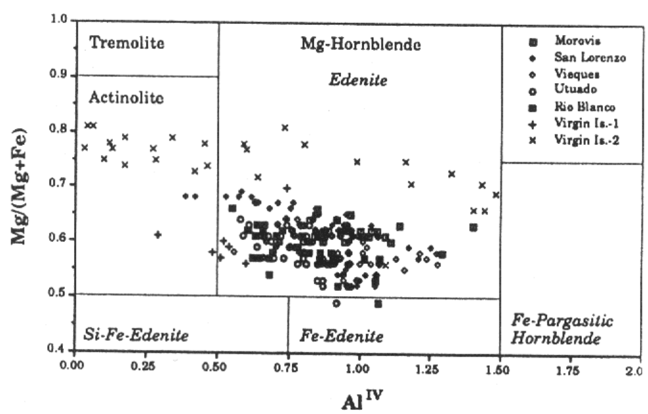

Figure 2. Compositions of hornblende from intrusive granitoids of the eastern Greater Antilles island arc. Modified IMA classification of calcic hornblendes (Leake, 1978; Hammarstrom and Zen, 1986). Italicized type is nomenclature for (Na + K) ≥ 0.50; plain type is for (Na + K) ≤ 0.50. Virgin Is.-1, analyses in Table 1; Virgin Is.-2, analyses in Table 2.

Table 1. Hornblende Analyses, Eastern Greater Antilles Granitoids

Pluton	Morovis	San Lorenzo	Vieques	Utuado	Rio Blanco	Virgin Is.
Samples (n)	3	4	4	5	3	3
Analyses (n)	25	49	43	42	33	12
SiO_2	46.35	47.23	46.69	47.87	48.24	50.78
TiO_2	1.27	1.23	1.21	1.23	1.04	0.55
Al_2O_3	7.64	7.35	7.35	7.18	6.81	5.69
Cr_2O_3	0.01	0.00	0.01	0.02	0.00	0.00
FeO_T	12.84	12.81	13.70	13.31	14.36	14.15
MnO	0.82	0.94	1.11	0.74	0.86	1.37
MgO	11.63	11.39	10.81	10.57	11.46	12.11
CaO	12.30	11.96	12.15	12.26	11.77	11.48
Na_2O	1.63	1.62	1.40	1.43	1.35	1.18
K_2O	0.85	0.68	0.63	0.73	0.33	0.39
F	0.34	0.14	0.12	0.23	0.07	0.06
Sum	95.69	95.36	95.20	95.57	96.31	97.43
Cations Based on 23 Oxygens:						
Si	7.00	7.12	7.09	7.20	7.20	7.45
Al^{iv}	1.00	0.88	0.91	0.80	0.80	0.55
Al^{vi}	0.36	0.43	0.41	0.48	0.40	0.44
Ti"	0.14	0.14	0.14	0.14	0.12	0.05
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.62	1.62	1.74	1.68	1.80	1.73
Mn	0.10	0.12	0.14	0.09	0.11	0.14
Mg	2.62	2.56	2.45	2.37	2.55	2.65
Ca	1.99	1.93	1.98	1.98	1.88	1.80
Na	0.48	0.47	0.41	0.42	0.39	0.34
K	0.16	0.13	0.12	0.14	0.06	0.07
Sum	15.48	15.40	15.39	15.30	15.31	15.22
Al^T	1.36	1.31	1.32	1.28	1.20	0.99
Sigma (Al^T)	0.08	0.19	0.11	0.14	0.15	0.12
Pressure (kbar)	2.92	2.67	2.72	2.52	2.12	1.06
Depth (km)	10.25	9.37	9.54	8.84	7.42	3.72

batholith. A plot of Al^T vs. Al^{iv} yields a least-square regression line for these analyses of $Al^{iv} = -0.54 + 1.09Al^T$, $r^2 = 0.94$. The slope of this equation is steeper than the one reported by Hammarstrom and Zen (1986), possibly because of generally lower Al^{vi} content and more restricted range of Al^T, however, its linearity and similarity to the Hammarstrom and Zen curve suggest that the barometer is also applicable to these Caribbean plutonic rocks.

The range of hornblende compositions in the six plutons is shown on Figure 2, a modified version of the IMA classification of calcic amphiboles (Leake, 1978; Hammarstrom and Zen, 1986). Each point represents an individual spot analysis. Essentially all of the analyses used in the pressure calculation are edenites. Samples from a gabbro, a diorite, and a tonalite from the Virgin Islands batholith are also plotted (Fig. 2; Table 2) but were excluded from the calculations because of the previously noted compositional and mineralogical constraints imposed by the geobarometer (see subsequent discussion of Virgin Islands batholith).

DESCRIPTION OF INDIVIDUAL PLUTONS

General

All of the intrusions discussed in this report, with the exception of the Vieques pluton, have been the subject of field mapping and at least reconnaissance major element and K-Ar geochronologic studies (references for each pluton is given below). Unfortunately, only a limited amount of published modal, mineralogical, or textural data are available on the plutons (Nelson, 1968; Chen, 1969). It is therefore difficult to evaluate the distribution, abundance, and mineral assemblages of the main rock types in each of the plutons. However, major element analyses and calculated CIPW norms provide an alternative basis for characterizing the plutons according to major rock types. Figure 3 is a plot of the normative proportions of quartz, plagioclase, and K-feldspar utilizing the IUGS classification scheme (Streckeisen, 1976). This normative plot approximates closely the standard modal plot because there are only minor differences in the specific gravity of the three end components and because the K-feldspars in the plutons is only sparsely perthitic.

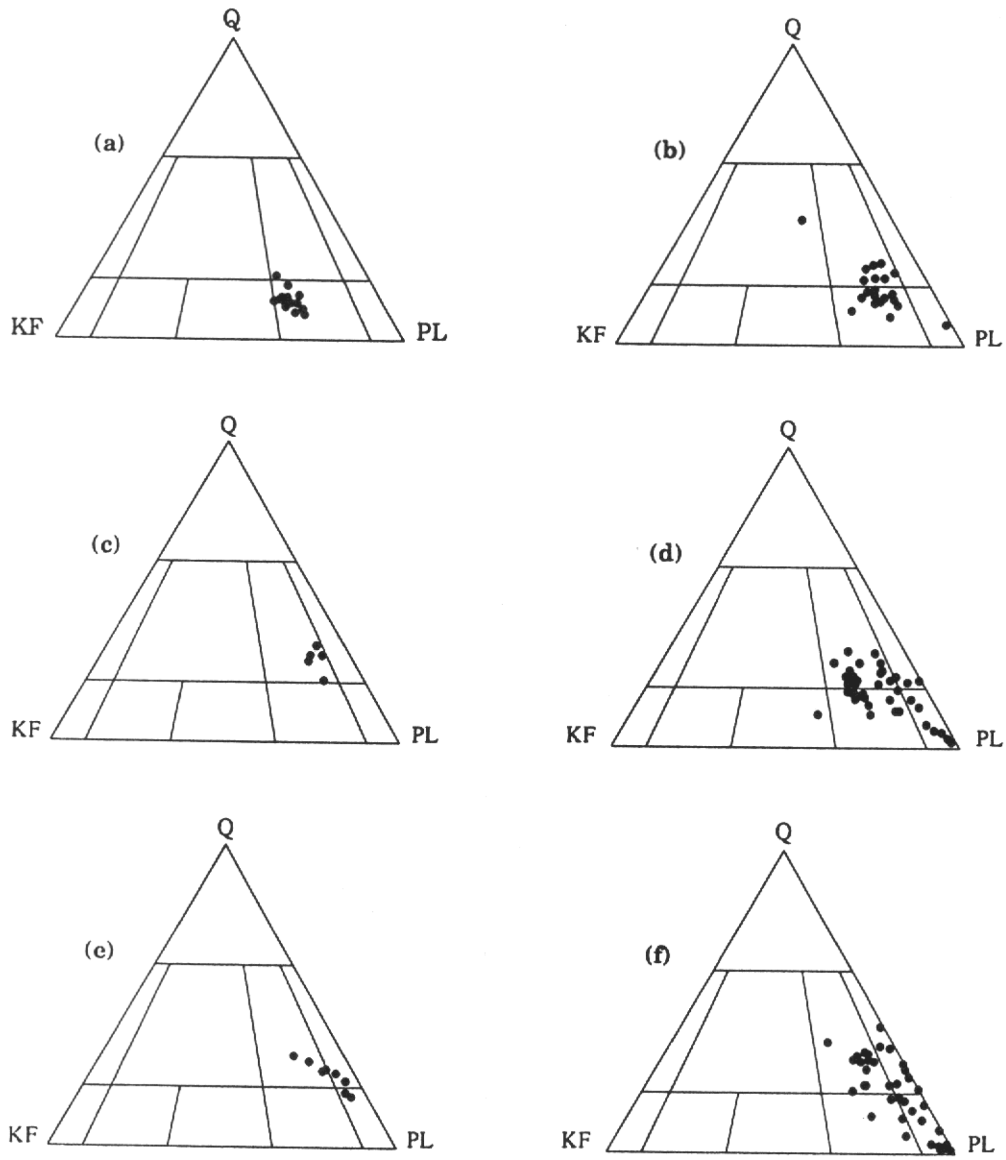

Figure 3. Quartz-K-Feldspar-Plagioclase compositions of eastern Greater Antilles granitoid rocks. All plotted data are CIPW norms except Fig. 3c which are modal compositions. (a), Morovis stock (Kesler and Sutter, 1979); (b), San Lorenzo batholith (Kesler and Sutter, 1979); (c), Vieques pluton (this report); (d), Utuado pluton (Chen, 1969); (e) Rio Blanco stock (Kesler and Sutter, 1979); (f), Virgin Islands batholith (Longshore, 1965). Classification field boundaries are from Streckeisen (1976).

Morovis Stock

The Morovis stock (Fig. 4) is a relatively small unit of about 20 km^2 that is intrusive into the potassic Rio Orocovis Formation (Berryhill, 1965; Lidiak, 1965). The stock is medium grained and texturally homogeneous and contains conspicuous laths of K-feldspar and subparallel crystals of hornblende throughout. Normative data (Fig. 3a) indicate that the stock consists primarily of quartz monzodiorite. The stock is the oldest of the intrusives considered in this report, having a K-Ar date on hornblende of 88 Ma (Cox and others, 1977), and is one of the most potassic intrusives in the eastern Greater Antilles. The average K_2O content is 3.9 percent (Kesler and Sutter, 1979).

The mineral assemblage is quartz, zoned plagioclase (An_{45}-An_{35}), K-feldspar, hornblende, chloritized biotite, sphene, magnetite, and zircon. Quartz is mainly intergranular and commonly adjacent to hornblende. Hornblende is greenish-brown and is mainly subhedral to euhedral, zoned, and less commonly poikilitic.

San Lorenzo Batholith

The San Lorenzo batholith (Fig. 5) is the largest pluton in the eastern Greater Antilles having an outcrop extent of about 500 km^2. It is a complex intrusion and has been divided into three mappable units: granodiorite-quartz diorite (comprising 75 percent of the batholith), a quartz monzonite-quartz diorite, and a small unit of diorite-gabbro (Cox and others, 1977). K-feldspar is a prominent mineral in most of the granitoid rocks. The available normative compositions (Fig. 3b) of samples from the two main granitoid units plot in the quartz monzodiorite and granodiorite fields. Some of the rocks are distinctly potassic and similar to rocks of the Morovis stock. An average K-Ar date on hornblende from the main granodiorite-quartz diorite unit is about 73 Ma (Cox and others, 1977). The batholith has had a more complex history;

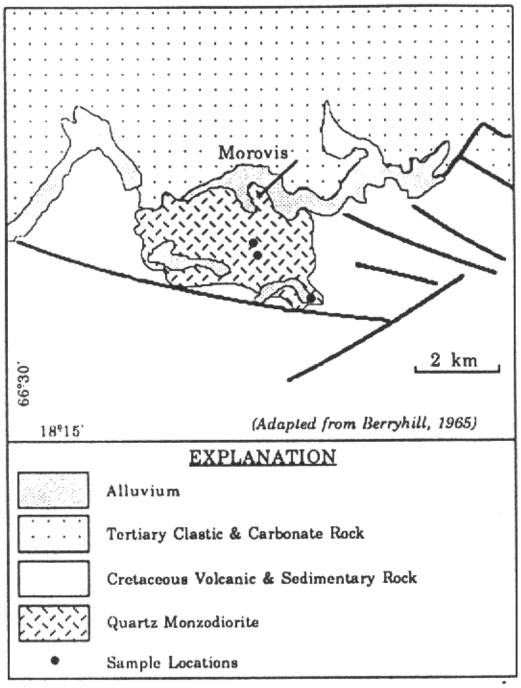

Figure 4. Generalized geologic map of Morovis stock.

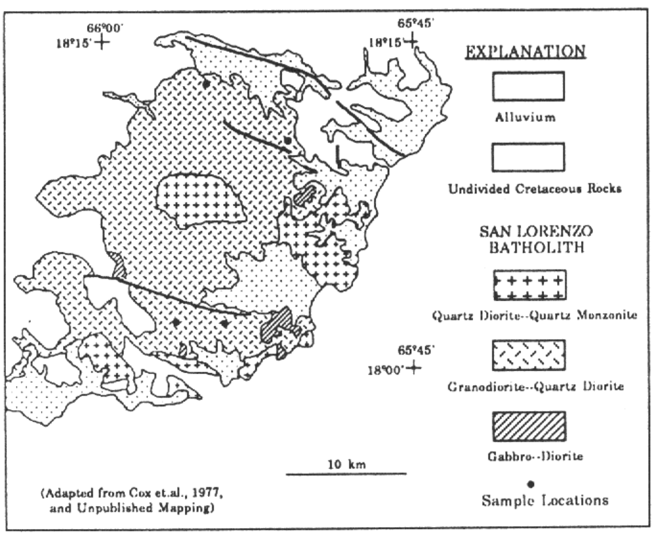

Figure 5. Generalized geologic map of San Lorenzo batholith.

for example, the diorite-gabbro unit yields K-Ar ratios older than 78 Ma and the quartz monzonite-quartz diorite unit has values as low as about 66 Ma (Cox and others, 1977). The average K_2O content of the main-phase granodiorite-quartz diorite is 2.5 percent (Kesler and Sutter, 1979).

Only samples from the main-phase granodiorite-quartz diorite unit were studied in this report. They are mainly medium to coarse grained and only moderately porphyritic. Samples from which hornblende was analyzed contain the assemblage quartz, zoned plagioclase (An_{40}-An_{50}), K-feldspar, hornblende, biotite, sphene, magnetite, apatite, and zircon.

The hornblende is mainly euhedral to subhedral, some with locally resorbed edges, and poikilitic. In one of the unanalyzed samples, the typical greenish-brown hornblende is partially replaced by a light green-blue amphibole having uneven extinction or by a complex intergrowth of actinolite, chlorite, epidote and an opaque mineral.

Vieques Pluton

The Vieques pluton (Fig. 6) crops out in an area of about 80 km^2 in the western part of Isla Vieques, but it probably underlies most of the island. The pluton has been mapped only in reconnaissance (Briggs and Akers, 1965) and chemical analyses are not yet available. The few modal analyses that are available (Fig. 3c) plot in the granodiorite field and these determinations are in agreement with observations by the author that granodiorite is the main phase of the pluton. However, portions of the pluton are not accessible because of military restrictions. K-feldspar is a subordinate phase in most of the rocks.

Rock samples are typically medium to coarse grained and moderately porphyritic with distinctly aligned hornblende crystals. In thin section, the primary mineral assemblage consists of quartz, zoned plagioclase (An_{40}-An_{50}), K-feldspar (subordinate), hornblende, biotite, magnetite, sphene (rare), and zircon. Hornblende is mainly poikilitic and moderately zoned. In some sections the primary greenish-brown hornblende is partly to completely replaced by light green amphibole, chlorite, epidote, and an opaque mineral.

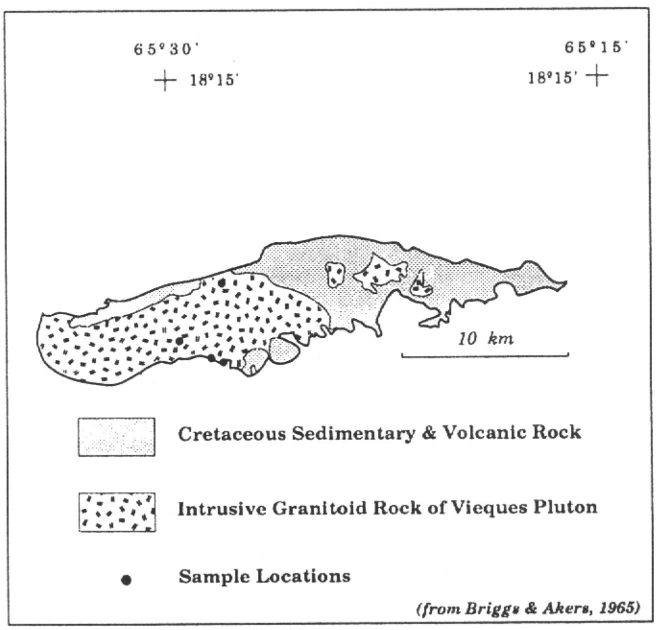

Figure 6. Generalized geologic map of Vieques pluton.

Utuado Pluton

The Utuado pluton (Fig. 7) occupies an area of about 200 km^2 and is a composite pluton that is elongate in the direction of the regional structure. The main phase of the pluton has been mapped as quartz diorite, granodiorite, and quartz monzonite (Weaver, 1958; Chen, 1969; Cox and others, 1977) which has an average K-Ar hornblende date of 67 Ma (Cox and others, 1977). The CIPW normative plot (Fig. 3d) indicates that the pluton is comprised of gabbro, diorite, tonalite, quartz monzodiorite, and granodiorite. Many of the rocks have a distinct potassic signature, and the average K_2O content of granitoid rocks from the main-phase pluton is 2.4 percent (Chen, 1969).

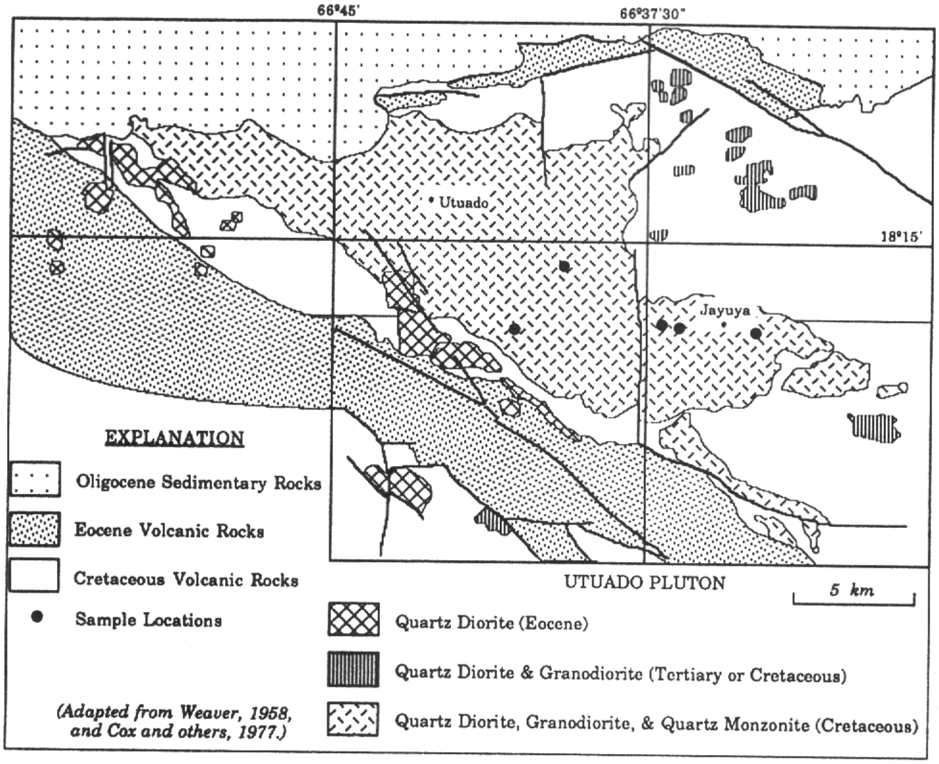

Figure 7. Generalized geologic map of Utuado pluton

The granitoid rocks are mainly medium to coarse grained and equigranular. Samples studied in this report have a generally consistent mineral assemblage of quartz, zoned plagioclase (An_{25}-An_{40}), K-feldspar, hornblende, biotite, sphene, and magnetite. The biotite is commonly chloritized and both biotite and hornblende are locally replaced by intergrown chlorite, epidote, and opaques. The analyzed hornblende is moderately zoned, euhedral to subhedral, poikilitic, and some crystals show resorption effects along rims.

Rio Blanco Stock

The Rio Blanco stock (Fig. 8) crops out north of the San Lorenzo batholith in an area of about 20 km^2. Seiders (1971) mapped the stock as a quartz diorite and diorite. CIPW norms (Fig. 3e) plot within the quartz diorite, tonalite, and granodiorite fields. These rocks contrast with the other Puerto Rican intrusives discussed here in containing less normative and modal K-feldspar. The average K_2O content is 1.2 percent (Kesler and Sutter, 1979). Co-existing hornblende and biotite yield concordant K-Ar dates of 46 Ma (Cox and others, 1977).

The rocks are medium to coarse grained and equigranular to porphyritic with phenocrysts of both plagioclase and hornblende. Aligned mafic inclusions and large hornblende megacrysts are abundant in some samples. The minerals present are quartz, complexly zoned plagioclase (An_{35}-An_{50}), K-feldspar, hornblende, biotite, magnetite, sphene (±), apatite, and zircon. Glomeroporphyritic aggregates consist of hornblende, plagioclase, biotite, and magnetite. Hornblende occurs both as large crystals with slightly poikilitic cores and thin exsolution lamellae, surrounded by complexly poikilitic zones, and clear, slightly zoned margins, and as small, slightly zoned, clear crystals. Only the latter were analyzed. Replacement patches of chlorite, epidote, and opaques (±) are minor.

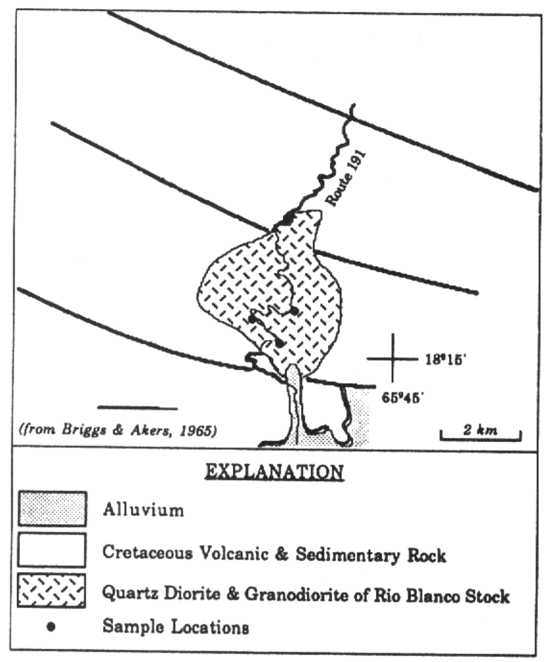

Figure 8. Generalized geologic map of Rio Blanco stock.

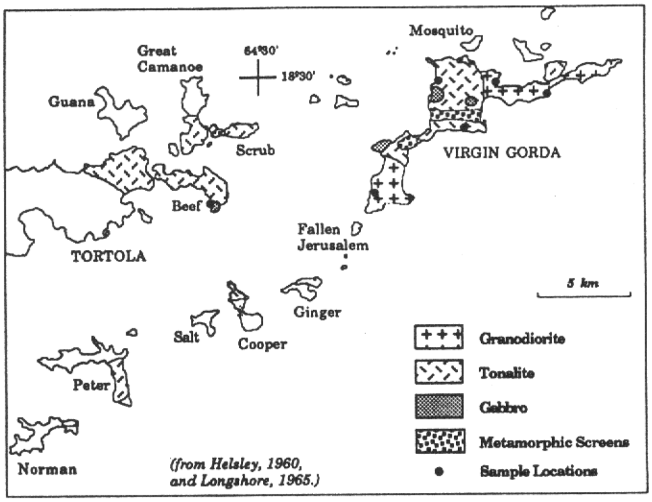

Figure 9. Generalized geologic map of Virgin Islands batholith.

Virgin Islands Batholith

The Virgin Islands Batholith (Fig. 9) is exposed mainly on the islands of Virgin Gorda, Tortola, Great Camanoe, Scrub , and Peter. The distribution of the contact aureole and magnetic anomaly patterns suggest that large portions of the batholith are submerged and that the intrusive rocks on each of the islands are interconnected and part of a composite batholith having an extent of about 160 km^2 (Helsley, 1960; Longshore, 1965). The batholith was emplaced as a discordant, flat-lying, sill-like body prior to regional tilting of about 90^0 about an axis approximately parallel to the strike of the enclosing sedimentary rocks (Helsley, 1960; Longshore, 1965). The western part of the batholith is intrusive mainly into the Cretaceous Tutu Formation; in the eastern portions it is progressively more discordant and intrusive into the 7,600-meter-thick Eocene Tortola Formation.

The main rock types of the batholith consist of gabbro (10%), diorite and tonalite (65%), and granodiorite (65%) with the main compositional and textural phases commonly being gradational (Helsley, 1960; Longshore, 1965). Figure 3f shows the normative compositions. The granitoid rocks form a generally low-potassic suite and have an average K_2O content of about 1.2 percent (Longshore, 1965). K-Ar dates from the eastern part of the batholith indicate emplacement at about 35 Ma (Cox and others, 1977; Kesler and Sutter, 1979).

The rocks are texturally diverse and vary from fine to coarse grained, equigranular to porphyritic, and massive to layered. Of the samples studied in this project, only three were included in the pressure calculations (Table 1). Their primary mineralogy consists of quartz, zoned plagioclase (An_{35}-An_{45}), K-feldspar, hornblende, chloritized biotite, magnetite, sphene, apatite, and zircon. The hornblende is unaltered, medium greenish-brown, slightly zoned, subhedral, and free of inclusions. The biotites are commonly chloritized and some are altered to chlorite + epidote.

Three other amphiboles (Table 2) were not included in the calculations. Samples BI-22 and VG-168 are hornblende from a quartz-free gabbro and a quartz-free diorite, respectively. The hornblende in thin section is colorless to light green brown and occurs as marginal to interstitial replacements of primary hypersthene and augite. The compositions indicate that the crystals are aluminous magnesio-hornblende. The third sample (VG-329), an amphibole from a tonalite having a largely recrystallized texture is compositionally an actinolite (Table 2, Fig. 2). The actinolite is colorless to light green, forms elongate crystals with acicular edges, and has uneven to patchy extinction.

Table 2.Magnesio-hornblende and actinolite analyses, Virgin Islands batholith

Sample Rock Mineral	BI-22 Gabbro Mg-Hornblende	VG-168 Diorite Mg-Hornblende	VG-329 Tonalite Actinolite
Analyses (n)	6	4	18
SiO_2	46.35	47.23	46.69
TiO_2	1.16	1.51	0.68
Al_2O_3	10.68	10.76	2.82
Cr_2O_3	0.04	0.01	0.00
FeO	8.73	10.45	8.52
MnO	0.18	0.13	0.39
MgO	12.33	13.40	15.87
CaO	13.39	12.26	12.05
Na_2O	1.54	2.62	1.32
K_2O	0.19	0.28	0.23
F	0.06	0.07	0.31
Sum	92.82	98.32	94.14
Cations Based on 23 Oxygens:			
Si	6.76	6.75	7.69
Al^{iv}	1.24	1.25	0.31
Al^{vi}	0.68	0.58	0.18
Ti	0.13	0.16	0.08
Cr	0.00	0.00	0.00
Fe	1.11	1.26	1.06
Mn	0.02	0.02	0.05
Mg	2.77	2.88	3.50
Ca	2.18	1.89	1.91
Na	0.45	0.73	0.38
K	0.04	0.05	0.04
Sum	15.39	15.57	15.20
Al^T	1.92	1.83	0.49
Sigma (Al^T)	0.28	0.16	0.16

The presence of several augite relicts indicates that the amphibole is of replacement origin. It is clear that none of the amphiboles listed in Table 2 equilibrated with a quartzose calc-alkalic magma.

DISCUSSION

The total Al content of hornblende and the corresponding calculated pressures at which hornblende crystallized show a distinguishable trend of decreasing Al^T content and pressure with decreasing K-Ar date of the plutons (Tables 1 and 3). Although there is some overlap in the Al^T values at the one sigma level, particularly for the higher Al^T values, as well as uncertainty in the K-Ar ages at which the plutons were emplaced, the overall trend in the data seems clear.

Table 3 shows that there is a progressive decrease in both pressure and K-Ar date of plutons from the Morovis stock (oldest), through the San Lorenzo batholith, Utuado pluton, and Rio Blanco stock, to the Virgin Islands batholith (youngest). The pressures (and inferred depths of emplacement) are: Morovis, 2.9 kbars (10.3 km); San Lorenzo, 2.7 kbars (9.4 km); Utuado, 2.5 kbars (8.8 km); Rio Blanco, 2.1 kbars (7.4 km); and Virgin Islands, 1.1 kbars (3.7 km).

An independent check of the pressure data is Longshore's (1965) estimate of 1-3 kbars for the formation of the contact aureole associated with the Virgin Islands batholith. The maturation of organic material in Puerto Rican sedimentary rocks (Hayes and others, 1986) has also been used to infer a shallow

Table 3. Relation among pressure and depth of emplacement, K-Ar date, and average K_2O content of eastern Greater Antilles granitoid rocks and their estimated rate of uplift

Pluton	Pressure (kbars)	Depth* (km)	K-Ar Date (Ma)	K_2O (%)	Uplift Rate (cm/yr)
Morovis	2.92	10.3	88	3.9	0.012
San Lorenzo	2.67	9.4	73	2.5	0.013
Utuado	2.52	8.8	67	2.4	0.013
Rio Blanco	2.12	7.4	46	1.2	0.016
Virgin Is.	1.06	3.7	35	1.2	0.011

*Depth based on a density of 2.85 gm/cm^3.

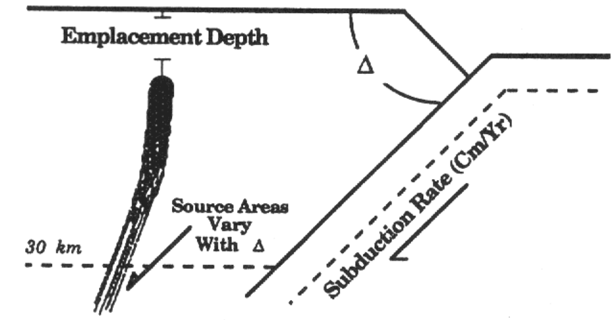

Figure 10. Schematic diagram showing proposed relation of depth of emplacement of plutons to angle and rate of subduction. An increase in rate of subduction causes a flattening of the angle of subduction (Δ) which results in a change in magma source areas, less interaction of the magma with the upper lithosphere, and a shallower depth of plutonic emplacement.

depth of burial of the sedimentary and volcanic sequence. There is, however, some uncertainty in such estimates as an appropriate geothermal gradient and an applicable temperature/reflectance curve must be assigned. Utilizing mean reflectance values of 1.5-2.5 (Hayes and others, 1986), the temperature/reflectance curves of Barker and Pawlewicz (1986), and a hypothetical geothermal gradient of 50^{0}C/km, yields a depth of burial of about 5-6 km for the Eocene-late Cretaceous and middle Cretaceous sequences. Lower geothermal gradients of 30-40^{0}C/km yield values more closely comparable to the Al^T data.

A second important correlation summarized in Table 3 is that there is also a relationship among the composition (as expressed in average K_2O content), depth of emplacement, and K-Ar date. The older Morovis, San Lorenzo, and Utuado intrusives are all more potassic than the less-potassic and younger Rio Blanco and Virgin Islands intrusives (Table 3). Of the former, the Morovis is the oldest and most potassic and was emplaced at the greatest depth. There is thus a pattern of evolutionary change in both composition and depth of emplacement during the main plutonic phases of eastern Greater Antilles island arc development.

TECTONIC IMPLICATIONS

The pressure data presented here indicate that about 10 km of unroofing occurred in portions of the eastern Greater Antilles since late Cretaceous time. Assuming a simple linear relationship between depth (pressure) and age, a surprisingly consistent rate of uplift of 0.01-0.02 cm/yr for all five plutons is obtained (Table 3). Although this rate is decidedly minor compared to estimated lateral plate movements in the Caribbean during the same time span (Burke, 1988; Donnelly, 1989) and to vertical movements in other tectonically active areas (Zen, 1985), it is nevertheless reflective of the tectonic history and perhaps characteristics of active oceanic orogenic areas.

A further consequence is the inter-relation among depth of plutonic emplacement, K-Ar date, and average K_2O content of the plutons. The reason for this relationship is not entirely straight forward and may be the result of a variety of factors. Previous work on both the volcanic (Lidiak, 1972) and the intrusive rocks (Kesler and Sutter, 1979) of Puerto Rico has shown that the K_2O content changes through time and may be related to changes in depth of magma generation. The new Al^T hornblende data is clear indication that pressure (depth) is an important factor in the equation.

My current interpretation is that the depth and composition parameters are related to magma generation associated with a change in the angle of the Benioff zone and a change in the rate of subduction. The earlier plutons are derived and emplaced by interaction of a steeply-dipping subduction zone. An increased rate of subduction results in flattening of the subduction angle, a changing source area of magma generation, shallower depths of pluton emplacement, and possibly less interaction of the up-welling magma with the enclosing upper lithosphere. These relations are shown schematically on Figure 10. The proposed decrease in subduction angle is, in general, consistent with changes in relative motions of the major plates (Pindell and others, 1988; Donnelly, 1989) during the interval 100 to 35 Ma. Accordingly to Donnelly (1989), the rate of convergence changed from about 6 cm/yr 102 to 72 Ma ago to 12-13 cm/yr between 72 and 35 Ma ago.

Other parameters such as age of the subducted lithosphere, thermal regimes, and magma viscosity also need to be evaluated to obtain a better understanding of evolution of the plutons in the eastern Greater Antilles island arc.

Acknowledgments. I thank John Longshore of Humboldt State University for providing some of the Virgin Islands samples. Dave Little of Ohio State University helped in the use of the electron probe microanalyser.

REFERENCES CITED

Barker, C. E., and Pawlewicz, M. J., 1986, The correlation of vitrinite reflectance with maximum temperature in humic organic matter, *in* Buntebarth, G., and Stegena, L., eds., Lecture notes in earth sciences: Berlin, Springer-Verlag, v. 5, paleogeothermics, p. 79-93.

Berryhill, H. L., Jr., 1965, Geology of the Ciales quadrangle, Puerto Rico: U. S. Geol. Survey Bull. 1184, 116 p.

Boynton, C. H., Westbrook, G. K., Bott, M. H. P., and Long, R. E., 1979, A seismic refraction investigation of crustal structure beneath the Lesser Antilles island arc: Geophys. Jour. Royal Astron. Soc., v. 58, p. 371-393.

Briggs, R. P., and Akers, J. P., 1965, Hydrologic map of Puerto Rico and adjacent islands: U. S. Geol. Surv. Hydrol. Inv. Atlas, Map HA-197, scale 1:240,000.

Burke, K., 1988, Tectonic evolution of the Caribbean: Ann. Rev. Earth Planet. Sci., v. 16, p. 201-230.

Chen, J.-C., 1969, Petrological and chemical studies of Utuado pluton, Puerto Rico: Acta Geol. Taiwanica, v. 13, p. 21-41.

Cox, D. P., Marvin, R. F., M'Gonigle, J. W., McIntyre, D. H., and Rogers, C. L., 1977, Potassium-argon geochronology of some metamorphic, igneous, and hydrothermal events in Puerto Rico and the Virgin Islands: Jour. Research U. S. Geol. Survey, v. 5, p. 689-703.

Donnelly, T. W., 1989, Geologic history of the Caribbean and Central America, *in* Bally, A. W., and Palmer, A. R., eds.,

The Geology of North America--An overview: Boulder, Colorado, Geol. Soc. America, v. A, p. 299-321.
Donnelly, T. W., and 10 others, 1990, History and tectonic setting of Caribbean magmatism, *in* Case, J. E., and Dengo, G., eds., The Caribbean Region: Boulder, Colorado, Geol. Soc. America, v. H, p. (in press).
Donnelly, T. W., and Rogers, J. J. W., 1978, The distribution of igneous rocks throughout the Caribbean: Geol. Mijnb., v. 57, p. 151-162.
Donnelly, T. W., and Rogers, J. J. W., 1980, Igneous series in island arcs: the northeastern Caribbean compared with worldwide island-arc assemblages: Bull. Volcanol., v. 43-2, p. 347-382.
Edgar, A. D., Ewing, J. I., and Hennion, J., 1971, Seismic refraction and reflection in Caribbean Sea: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 833-870.
Fettke, C. R., 1924, The geology of the Humacao district, Porto Rico: New York Acad. Sci., Sci. Surv. Porto Rico and the Virgin Islands, v. II (2), p. 117-197.
Hammarstrom, J. M., and Zen, E., 1986, Aluminum in hornblende: an empirical igneous geobarometer: Am. Mineralogist, v. 71, p. 1297-1313.
Hayes, J. A., Larue, D. K., Joyce, J., and Schellekens, J. H., 1986, Puerto Rico: reconnaissance study of the maturation and source rock potential of an oceanic arc involved in a collision: Jour. Marine Pet. Geol., v. 3, p. 126-139.
Helsley, C. E., 1960, Geology of the British Virgin Islands [Ph. D. Dissertation]: Princeton, New Jersey, Princeton University, 219 p.
Hollister, L. S., Grissom, G. C., Peters, E. K., Stowell, H. H., and Sisson, V. B., 1987, Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons: Am. Mineralogist, v. 72, p. 231-239.
Kesler, S. E., and Sutter, J. F., 1979, Compositional evolution of intrusive rocks in the eastern Greater Antilles island arc: Geology, v. 7, p. 197-200.
Leake, B. E., 1978, Nomenclature of amphiboles: Mineralog. Mag., v. 42, p. 533-563.
Lidiak, E. G., 1965, Petrology of andesitic, spilitic, and keratophyric flow rock, north-central Puerto Rico: Geol. Soc. America Bull., v. 76, p. 57-88.
Lidiak, E. G., 1972, Spatial and temporal variations of potassium in the volcanic rocks of Puerto Rico: Caribbean Geol. Conf. Trans., v. 6, p. 203-209.
Longshore, J. D., 1965, Chemical and mineralogical variations in the Virgin Islands batholith and its associated wall rocks [Ph. D. Dissertation]: Houston, Texas, Rice University, 94 p.
Nelson, A. E., 1968, Intrusive rocks of north-central Puerto Rico: U. S. Geol. Survey Prof. Paper 600-B, v. p. B16-B20.
Officer, C. B., Jr., Ewing, J. I., Hennion, J. L., Harkrider, D. G., and Miller, D. E., 1959, Geophysical investigations in the eastern Caribbean--summary of the 1955 and 1956 cruises, *in* Ahrens, L. H., Press, F., Rankama, K., and Runcorn, S. K., eds., Physics and Chemistry of the Earth: v. 3, p. 17-109.
Pindell, J. L., Cande, S. C., Pitman, W. C., III, Rowley, D. B., Dewey, J. F., La Brecque, J., and Haxby, W., 1988, A plate-kinematic framework for models of Caribbean evolution: Tectonophysics, v. 155, p. 121-138.
Rutter, M. J., Van der Laan, S. R., and Wyllie, P. J., 1989, Experimental data for a proposed empirical igneous geobarometer: aluminum in hornblende at 10 kbar pressure: Geology, v. 17, p. 897-900.
Seiders, V. M., 1971, Geologic map of the El Yunque quadrangle, Puerto Rico: U. S. Geol. Survey Misc. Geol. Inv., Map I-658, scale 1:20,000.
Streckeisen, A. L., 1976, To each plutonic rock its proper name: Earth Sci. Rev., v. 12, p. 1-34.
Weaver, J. D., 1958, Utuado pluton, Puerto Rico: Geol. Soc. America Bull., v. 69, p. 1125-1142.
Zen, E., 1985, Implications of magmatic epidote-bearing plutons on crustal evolution in the accreted terranes of northwestern North America: Geology, v. 13, p. 266-269.